Hybrid Seesaw Leptogenesis and TeV Singlets (II)

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Outline

- A hybrid seesaw model
- Leptogenesis
  - Dynamics of leptogenesis
  - Enlarging the M_N window
- Constraint from $\mu \to e\gamma$
- Conclusions

Inverse Seesaw

$$y\ \ \Psi^C H l + m_\Psi\, \Psi^C \Psi + \mu\, \Psi\Psi$$

R.N. Mohapatra, PRL 56, 561 (1986);
R. N. Mohapatra & J. W. F. Valle, PRD 34, 1642 (1986).

- Inverse seesaw obtains SM neutrino mass by exchange of TeV scale singlets with sizable Yukawa couplings, which can be probed at colliders.
- Two issues with inverse seesaw:
  - Smallness of Majorana splitting, μ, is unexplained.
  - Successful leptogenesis is difficult to achieve.

A Hybrid Seesaw Model

$$\mathcal{L} \supset y\ \Psi^C H l + \kappa\, \phi_\kappa \Psi^C \Psi + \lambda\, \phi_\lambda \Psi N + \frac{1}{2} M_N\, N N$$

- Integrating out N: $y\ \Psi^C H l + \kappa\, \phi_\kappa \Psi^C \Psi + \frac{\lambda^2}{M_N} \phi_\lambda \Psi \phi_\lambda \Psi$

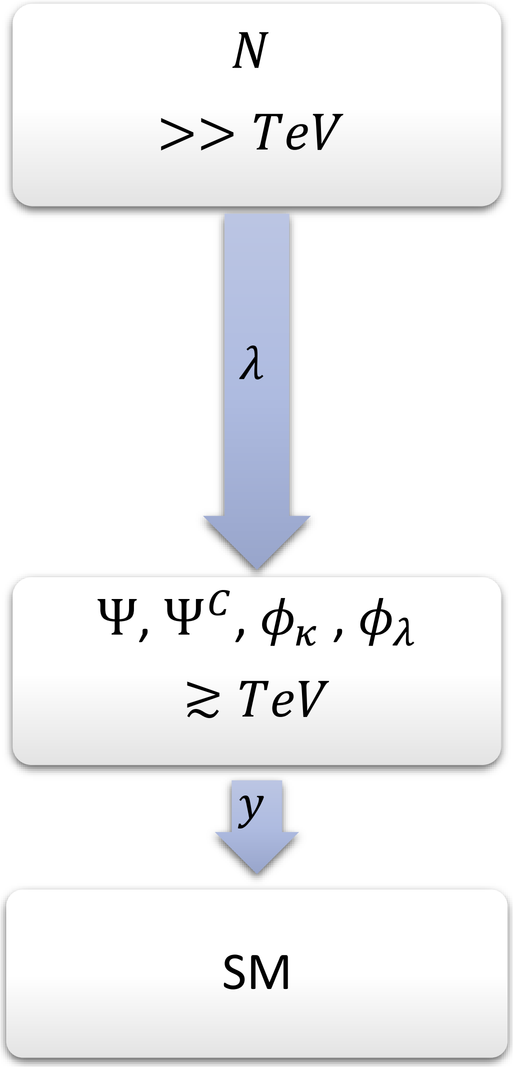
- $\phi_{\kappa,\lambda}$ get VEVs:

$$y\ \Psi^C H l + m_\Psi\, \Psi^C \Psi + \mu\, \Psi\Psi \qquad \text{(inverse seesaw)}$$

$$m_\Psi = \kappa \langle \phi_\kappa \rangle \qquad \mu = \lambda^2 \frac{\langle \phi_\lambda \rangle^2}{M_N}$$

- Neutrino mass:

$$m_\nu = \left(\frac{y\, v}{m_\Psi}\right)^2 \mu = \frac{\lambda^2 v^2}{M_N} \left(\frac{y \langle \phi_\lambda \rangle}{\kappa \langle \phi_\kappa \rangle}\right)^2$$



Leptogenesis - Big Picture

$T \sim M_N$

Asymmetry generation: $\Gamma(N \to \Psi\phi_\lambda) \neq \Gamma(N \to \Psi^*\phi_\lambda^*)$ | Washout by N inverse decays

↓

$m_\Psi \lesssim T \lesssim M_N$

Asymmetry in Ψ, ϕ_λ is shared with SM.

↓

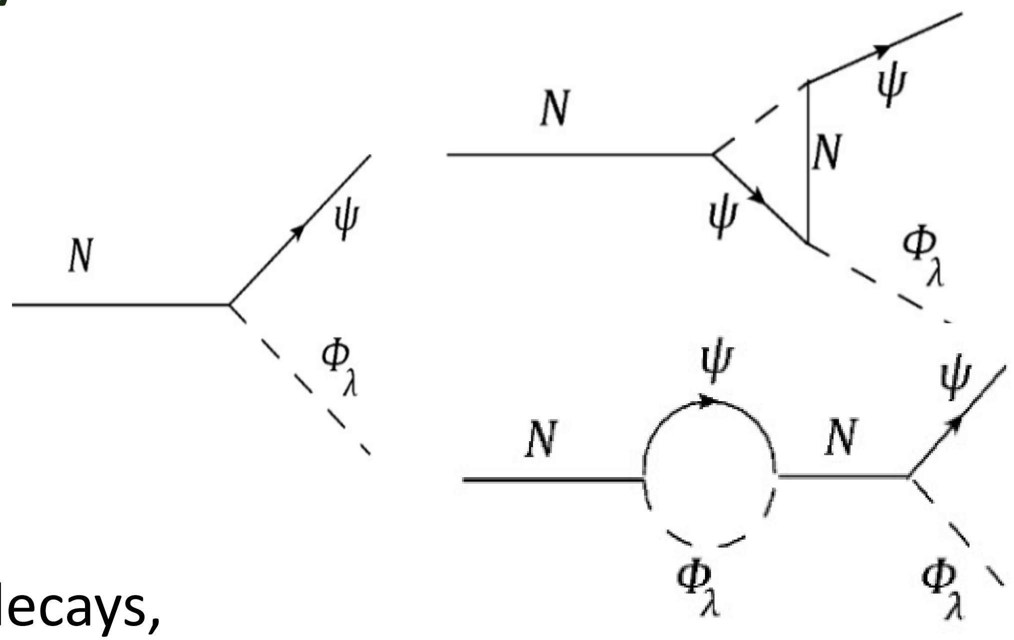
$T \sim m_\Psi$ ($\sim TeV$)

Important washout by Ψ, Ψ^C inverse decays

Leptogenesis- High Scale Dynamics

- Asymmetry generation from N decays:

$$\epsilon_N = \frac{\Gamma(N \to \psi\phi_\lambda) - \Gamma(N \to \psi^* \phi_\lambda^*)}{\Gamma_N} \sim \frac{\lambda^2}{16\pi}$$



- High scale washout dominated by N inverse decays, parameterized by: $K_N = \frac{\Gamma_N}{H}|_{T=M_N}$
- Net UV-asymmetry generated after N decays (assuming $K_N > 1$):

$$Y_{\Delta\Psi}^{UV} \sim 10^{-3} \frac{\epsilon_N}{K_N} \sim 10^{-2} \frac{M_N}{M_{Pl}}$$

TeV Scale Washout

- Washout dominated by Ψ, Ψ^C inverse decays (Blanchet, Hambye & Josse-Michaux, [arXiv:0912.3153 [hep-ph]])

$$K_\Psi^{eff} = \left(\frac{\mu}{\Gamma_\Psi}\right)^2 \frac{\Gamma_\Psi}{H}\Big|_{T=m_\Psi} \sim \frac{16\pi}{y^2}\frac{m_\Psi M_{Pl} m_\nu^2}{\sqrt{g_*} v^4}$$

- Asymmetry generated in UV gets an exponential suppression:

$$Y_{\Delta B} \sim Y_{\Delta\Psi}^{UV}\, e^{-K_\Psi^{eff}}$$

Leptogenesis-Enlarging the M_N window

- Standard type-I seesaw leptogenesis (without introducing degenerate masses or flavor effects) works only for $10^9\text{GeV} \lesssim M_N \lesssim 10^{15}\ GeV$.
- Lower bound of $M_N \gtrsim 10^9$GeV comes from the connection between neutrino mass and CP asymmetry (Davidson & Ibarra [hep-ph/0202239])

$$y\ NHl + \frac{1}{2} M_N\ NN$$

$$m_\nu \sim \frac{y^2 v^2}{M_N}$$

Standard seesaw: $\epsilon \sim \frac{y^2}{8\pi} \sim \frac{M_N m_\nu}{8\pi v^2} \gtrsim 10^{-7}$

Hybrid Seesaw: $\epsilon \sim \frac{M_N m_\nu}{8\pi v^2} \times \left(\frac{\kappa\langle\phi_\kappa\rangle}{y\langle\phi_\lambda\rangle}\right)^2 \gtrsim 10^{-7}$

$$M_N \gtrsim 10^9 GeV \times \left(\frac{y\langle\phi_\lambda\rangle}{\kappa\langle\phi_\kappa\rangle}\right)^2$$

$$y\ \Psi^C Hl + \kappa\ \phi_\kappa \Psi^C \Psi$$

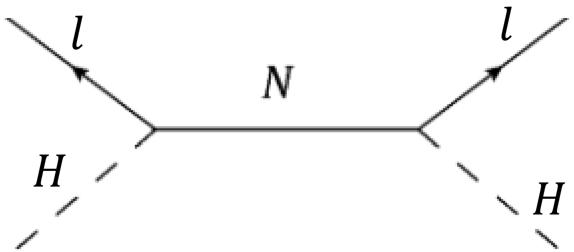
$$+ \lambda\ \phi_\lambda \Psi N + \frac{1}{2} M_N\ NN$$

$$m_\nu \sim \frac{\lambda^2 v^2}{M_N} \left(\frac{y\langle\phi_\lambda\rangle}{\kappa\langle\phi_\kappa\rangle}\right)^2$$

Leptogenesis- Enlarging the M_N window

- Upper bound of $M_N \lesssim 10^{15}$ GeV is due to washout from scattering getting large. (Buchmüller, Di Bari, Plümacher [hep-ph/0401240])

$$\Gamma_{scatt} \propto y^4$$



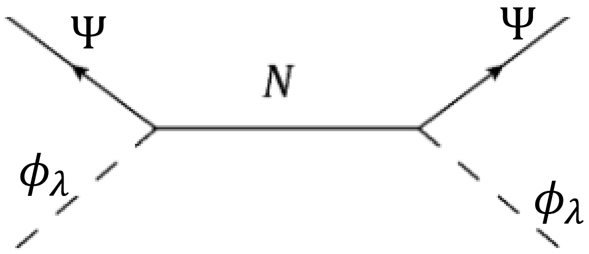
$$y\, NHl + \frac{1}{2} M_N\, NN$$

$$m_\nu \sim \frac{y^2 v^2}{M_N}$$

Hybrid seesaw:

$$\Gamma_{scatt} \propto \lambda^4$$

$$M_N \lesssim 10^{14} GeV \times \left(\frac{y\langle\phi_\lambda\rangle}{\kappa\langle\phi_\kappa\rangle}\right)^4$$

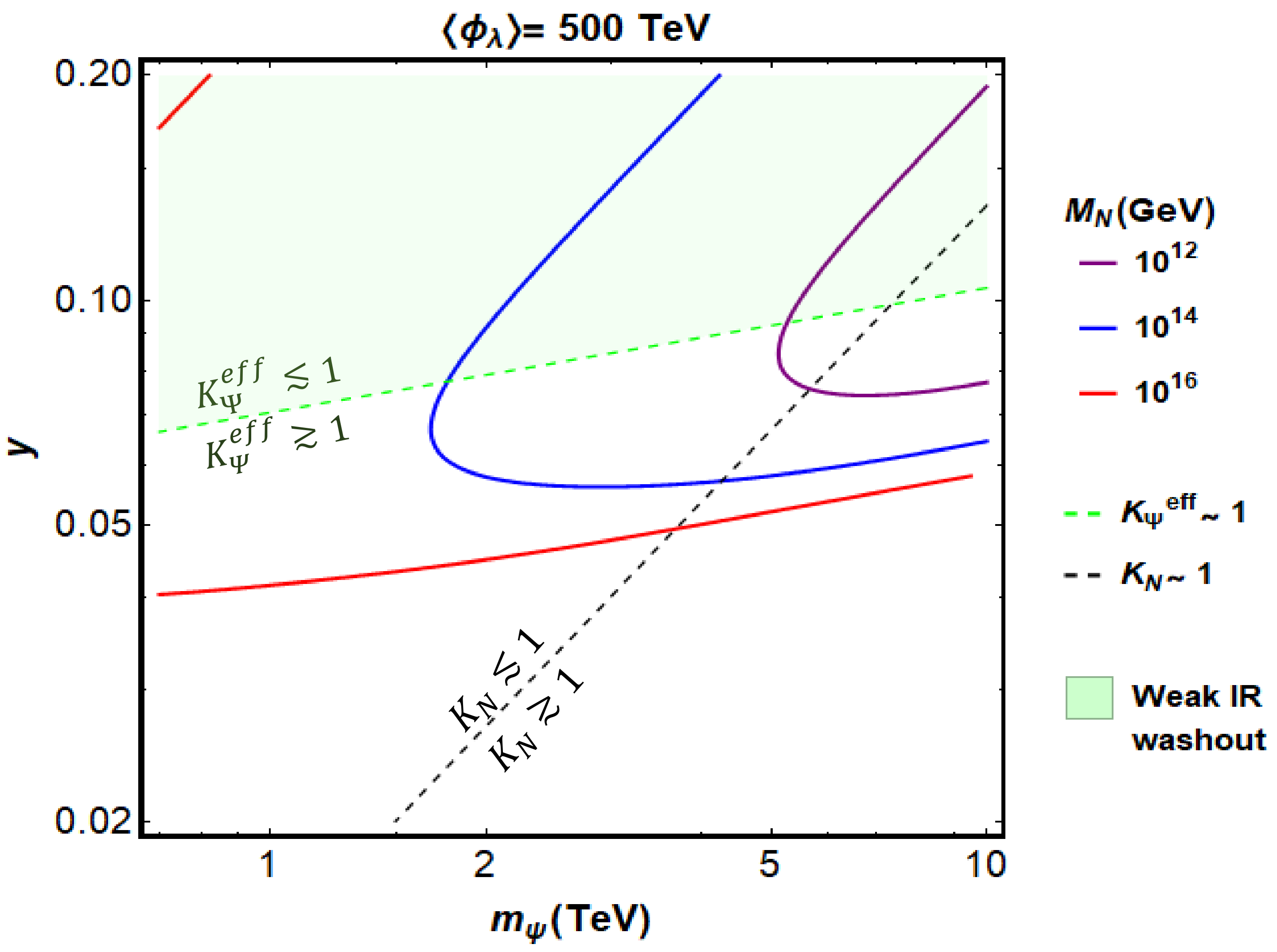


$$y\, \Psi^C H l + \kappa\, \phi_\kappa \Psi^C \Psi$$

$$+ \lambda\, \phi_\lambda \Psi N + \frac{1}{2} M_N\, NN$$

$$m_\nu \sim \frac{\lambda^2 v^2}{M_N} \left(\frac{y\langle\phi_\lambda\rangle}{\kappa\langle\phi_\kappa\rangle}\right)^2$$

Leptogenesis- parameter space

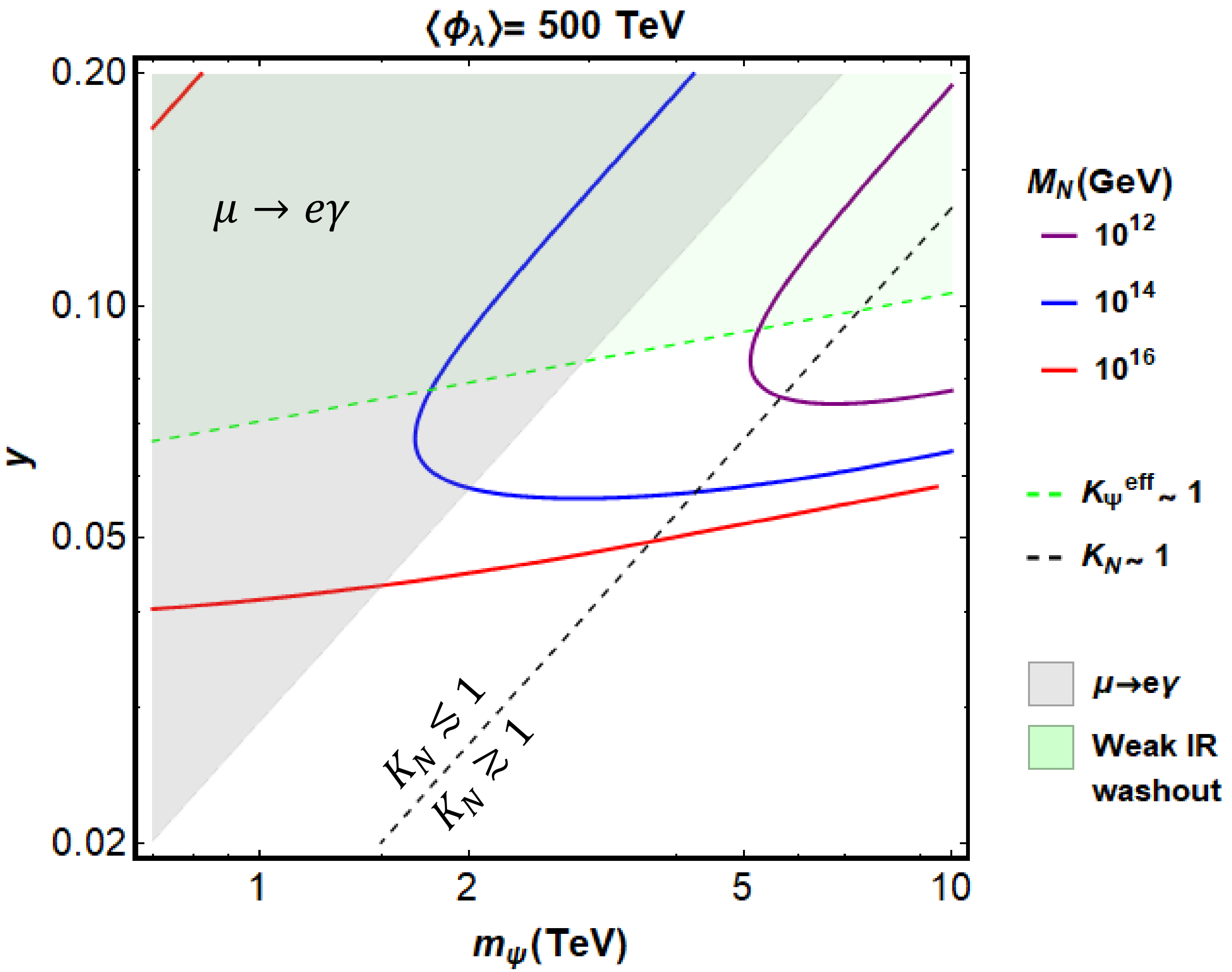


Constraint from $\mu \to e\,\gamma$

$$BR(\mu \to e\gamma) < 4 \times 10^{-13}$$ (MEG, 2016)

$$BR(\mu \to e\gamma) \simeq \frac{3\alpha_{em}}{8\pi}\left(\frac{yv}{m_\Psi}\right)^4$$

$$\frac{y}{m_\Psi} \lesssim \frac{0.027}{TeV}$$



Conclusions

- Our hybrid seesaw model explains the smallness of μ-term in inverse seesaw models and can give the right baryon asymmetry.
- Leptogenesis involves an interplay of high scale dynamics around M_N mass and TeV scale dynamics .
- The window for M_N mass consistent with leptogenesis can be enlarged going beyond the usual range of $M_N \sim 10^9 - 10^{15}$ GeV.
- TeV scale singlets of the presented model can be probed at the LHC or other low energy experiments such as $\mu \to e\gamma$.

Thank you!

Avoiding $\mu \to e\gamma$ bound

- The bound from $\mu \to \mathrm{e}\gamma$ can be avoided by requiring that lepton flavor symmetry is broken only at high scale $\sim M_N$.
- This makes Yukawa coupling matrix y diagonal in SM flavor basis, and all the flavor violation is encoded in λ.
- In low energy EFT, lepton flavor violation would be encoded in μ which is small.

UV Completion- Composite Higgs

- The structure of the hybrid seesaw model naturally arises in the composite Higgs setup. (Agashe, Hong & Vecchi, 2016)
  - A strongly coupled sector that preserves lepton number.
  - Lepton number broken an elementary N that couples weakly to the strong sector.
  - Role of $\Psi\phi_\lambda$ is played by an operator in the strong sector with the same quantum numbers.
  - Role of the modulation factor in the neutrino mass played anomalous dimensions.

UV Completion- A Gauge Model

- The structure can also arise from a weakly coupled gauge model:

$$\mathcal{L}_{\text{yuk}} = y_{a\alpha}\Psi_a^c H \ell_\alpha + \kappa_{ab}\Psi_a^c \Phi_\kappa \Psi_b + \lambda_{ai}\Psi_a \Phi_\lambda N_i + c_{ij} S' N_i N_j + y_\chi \chi\chi S$$

	$U(1)_{B-L}$	$U(1)_X$	spin
$\Psi^c_{a=1,2,3}$	$+1$	0	$1/2$
$\Psi_{a=1,2,3}$	0	α	$1/2$
$N_{i=1,2}$	0	-4α	$1/2$
Φ_κ	-1	$-\alpha$	0
Φ_λ	0	3α	0
χ	0	5α	$1/2$
S	0	-10α	0
S'	0	8α	0

Other constraints and Signals

- Mixing of singlet scalars with Higgs should be below $\sim 10\%$ (Robens & Stefaniak, 2016)

  satisfied with $O(1)$ couplings and $m_{\Phi_{\kappa,\lambda}} \gtrsim 1\, TeV$
- Potential collider signatures:
  - Ψ, Ψ^C can be produced in association with SM leptons via off-shell W. Final states would be opposite sign dileptons+jets or trileptons+missing energy. (Deppisch, Dev & Pilaftsis, 2015)
  - $\phi_{\kappa,\lambda}$ may be produced via the Higgs portal and then decay into Ψ, Ψ^C pair or into SM via Higgs.
- If $U(1)_{B-L}$ is gauged, precision electroweak bounds would require $\langle\phi_\kappa\rangle \gtrsim 7$ TeV. (Cacciapaglia, Csaki, Marandella & Strumia, 2006)
- Goldstone boson from spontaneous symmetry breaking of $U(1)_\lambda$:
  - would have a small coupling to the SM neutrinos $y_\pi \sim \frac{m_\nu}{\langle\phi_\lambda\rangle} \sim 10^{-13}\frac{TeV}{\langle\phi_\lambda\rangle}$
  - Higgs can decay to π_λ pair; safe from current Higgs invisible decay bounds. (Bonilla,Valle & Romão, 2015)